PERFORMANCE CHARACTERISTICS
OF A COMMERCIAL-GRADE BACK-LIGHTED THYRATRON

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Abstract

The performance characteristics of a single-gap, back-lighted-thyratron (BLT) design are reported. This switch, a sealed, ceramic-metal, hydrogen-filled, flashlamp-triggered device, operates over an internal pressure range of 100 to 500 mTorr (13.3 to 66.7 Pa). This characterization is based on the testing of three separate single-gap prototype devices (built by ITT) all with identical electrode geometries. Three different test circuits were used to evaluate the following switch characteristics: (1) DC holdoff, (2) delay, (3) jitter, (4) dI/dt, (5) recovery, (6) switch losses, and (7) rep-rate. These parameters were measured while varying switch voltage, current, and internal pressure. Some of the best performance characteristics include: peak switched current of 34 kA, peak switched voltage of 78 kV, minimum delay of 700 ns, minimum jitter of 15 ns, maximum dI/dt of 6.7×10^{11} A/sec, and minimum two-pulse recovery time of 470 μs.

Introduction

The back-lighted thyratron (BLT), a two-electrode, low-pressure, gas-discharge switch, is an optically triggered version of the pseudo-spark switch[1].

Development and testing of sealed, ceramic-metal BLTs, the topic of this paper, was initiated to improve the BLT's performance -- mainly by increasing the purity of the gas environment inside the switch. The prototype BLTs used in these tests were built by ITT using mostly standard ceramic-metal thyratron components and proven thyratron construction techniques. This effort, which began in 1987, produced significant improvement in switch performance over the demountable, O-ring sealed devices previously tested.

Switch Construction

A simplified cross-section drawing of the test switches is shown in Figure 1. It is a standard, hollow-electrode design with a centered electrode hole. The electrodes, made from a combination of copper and molybdenum pieces, are brazed to a ceramic insulator. The three critical electrode dimensions -- hole diameter, hole depth, and electrode separation -- are all 3.18 mm. These dimensions influence the voltage holdoff and triggering characteristics of the switch. A sapphire window, brazed to the cathode top plate, provides an aperture for UV light from the trigger source. This window is located off-axis to prevent premature metalization of the its interior surface. Metal vapor migrates from the cathode hole into the hollow-cathode space during switch operation. Offsetting the window was done at the cost of reducing light intensity in the cathode hole region, which makes triggering more difficult.

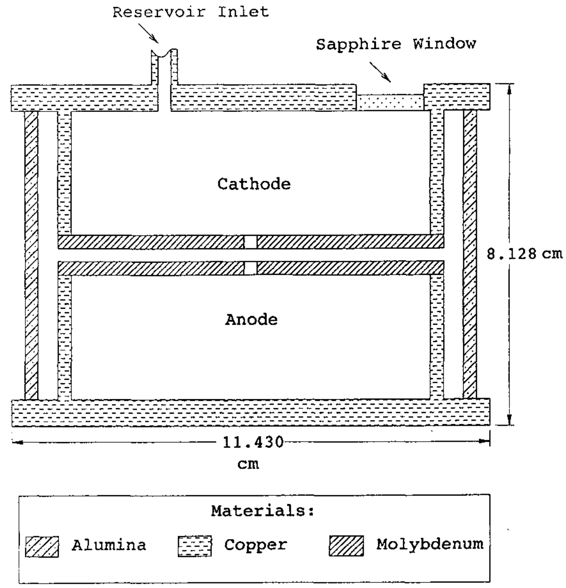

Figure 1. Simplified Cross Section of BLT

The first of the three test BLTs was filled with 500 mTorr (66.7 Pa) of hydrogen and then sealed. The two subsequent BLTs had built-in titanium reservoirs that were respectively housed in an external appendage and inside the hollow cathode. Switch pressure was determined by the reservoir current magnitude, which was calibrated against switch pressure during manufacturing. The external-appendage BLT also had an external built-in thermocouple pressure gauge.

Test Circuits

The test BLTs served as the output closing switches for three different test circuits. The low-impedance PFL circuit shown in Figure 2a was used to measure delay, jitter, recovery, dI/dt, and switch losses. The high-impedance RLC circuit shown in Figure 2b was used to measure the pressure-voltage characteristics, as well as delay and jitter. The low-impedance circuit shown in Figure 2c was used to perform rep-rate tests.

Voltage Operating Regime

For a fixed electrode geometry and gas type, maximum voltage holdoff is determined by the gas pressure. Figure 3 shows the maximum dc voltage held off by the test BLTs over the range of operating

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE
JUN 1991

2. REPORT TYPE
N/A

3. DATES COVERED
-

4. TITLE AND SUBTITLE
Performance Characteristics Of A Commercial-Grade Back-Lighted Thyratron

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Pulsed Power Technology Branch (F45) Naval Surface Warfare Center Dahlgren, VA 22448-5000

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License

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15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**4**	

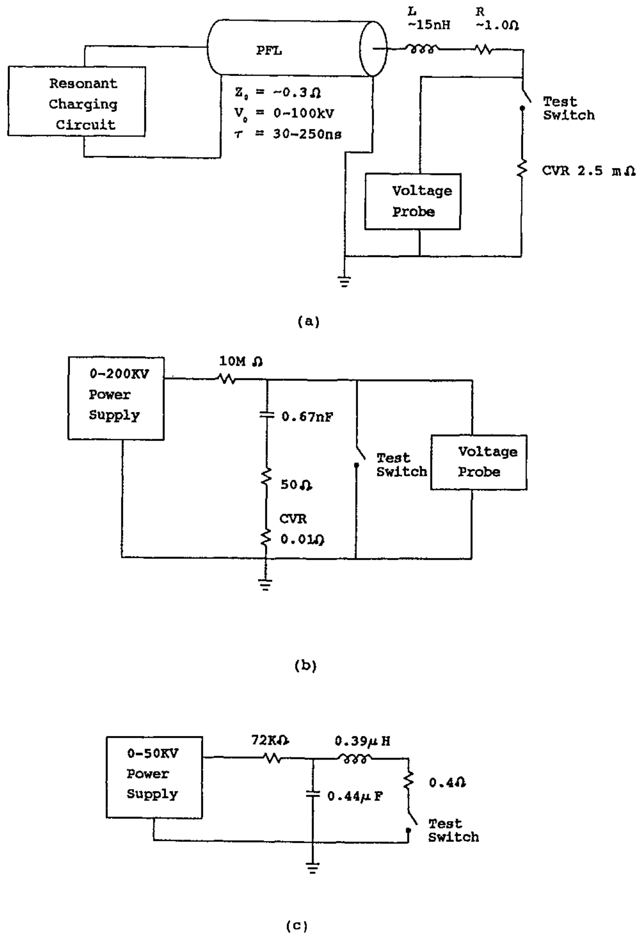

Figure 2. Test Circuits

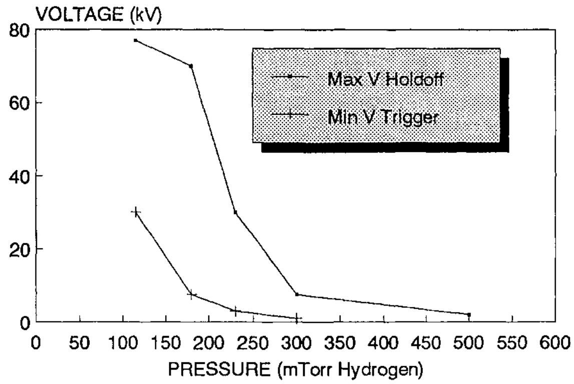

Figure 3. Voltage Operating Regime

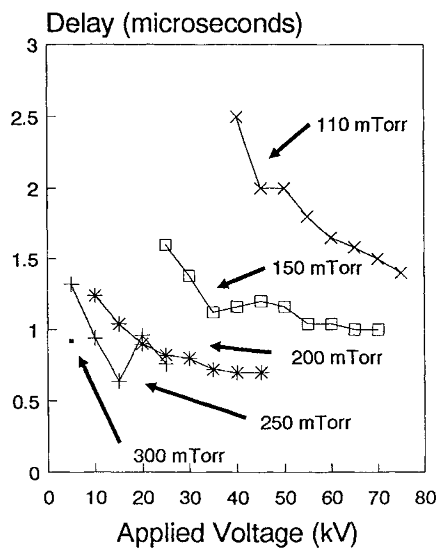

Figure 4. Delay

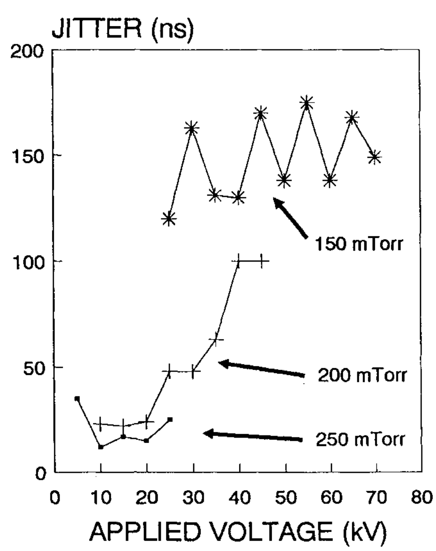

Figure 5. Jitter

pressures. Figure 3 also shows the pressure dependence of the minimum voltage at which the switch can be triggered for a fixed flashlamp light output. This curve is characteristic of the flashlamp system used in these tests adjusted to its maximum light output (approximately 17 mJ in the UV regime). The area between the above two curves specifies the operating voltage regime of the switch.

Delay and Jitter

Switch delay, in these tests, is defined as the time interval between the initial rise of the flashlamp current and the initial rise of the BLT current. Jitter is defined as one standard deviation in switch delay. Figures 4 and 5 respectively show the variation in delay and jitter with switch voltage and pressure.

The measured delay falls in the range of 0.6 μs to 2.5 μs. This relatively high delay is attributed to the relatively slow risetime of the flashlamp light output. Waveforms of the flashlamp current and the corresponding output light intensity is shown in Figure 6. The risetime of the light output is of the same order as the measured delays. Delay is reduced by either increasing the switch working pressure or voltage. Higher pressure, or higher gas density, facilitates the ionization of the gas in the discharge region because the particle mean free path is shorter. Likewise, higher voltage facilitates the discharge initiation by increasing the pre-discharge electric field in the hollow cathode.

Like delay, jitter increases with a decrease in switch pressure. This is explained by the increased mean free path. Since ionizing collisions are less frequent and ionizing avalanches less likely, not only is the average delay to breakdown longer, but the standard deviation of the delay will be larger. Unlike the delay, jitter was found to increase with the increase in voltage. It is clear that increased voltage will enhance the major processes that lead to switch closure, thus reducing the switch delay. The Schottky emission of electrons from the cathode surface will increase as a result of a higher electric field and because of increased heating from the impact of more energetic positive ions; also, the cross section for ionizing collisions between electrons and neutrals increases. However, there must be some other effect that leads to the jitter becoming larger with higher voltage. This may result from surface effects. There was evidence in the electrode surfaces that there had been occasional arcing; reference [1] mentions sporadic arcing that increases with current. Sporadic arcing, increasing with voltage and current, could increase the jitter.

Current Rate of Rise

Current rate of rise (dI/dt) was measured using the PFL test circuit at a switch pressure of 200 mTorr (26.7 Pa). A dI/dt range of 2.1×10^{11} A/sec to 6.7×10^{11} A/sec was measured for a peak switch current range of 10.4 kA to 34 kA (Figure 7). The relation between peak current and dI/dt remains linear over the above data range, indicating that the switch is not limiting dI/dt. It is likely that this high dI/dt is supported by field-enhanced thermionic emission of electrons from a surface layer of the cathode metal, heated by ion bombardment. In addition, metal vapor evaporates from the surface and lowers the mean free path for ionizing collisions.

Switch Losses

Switch losses were measured using the PFL test circuit[2] (specifically designed for this type of measurement), which is equipped with fast-response diagnostics capable of measuring the voltage drop across the switch as well as the switch current (Figure 8). The integrated product of the waveforms in Figure 8 yields the energy dissipated in the switch. Most of this energy was dissipated during the 50-ns, commutation phase of the switch. Switch loss, for a switch pressure of 200 mTorr, is plotted in Figure 9 as a function of initial energy stored in the 100-nF PFL. This relationship was found to be linear over the operating range of the circuit. Approximately 15% of the stored energy is dissipated in the switch. Increase of stored energy means increased current through the switch, which results in a larger area of the cathode feeding the discharge, hence a larger area that is melted[1]. The observation that the energy dissipated in the BLT is a fixed fraction of the energy stored is consistent with the model that the resistance of the switch, as a function of time, does not vary greatly with peak current. This effective switch resistance was found to be of the order of 100 mΩ. The high losses are the result of the switch resistance being significant in comparison to load resistance (~1 Ω).

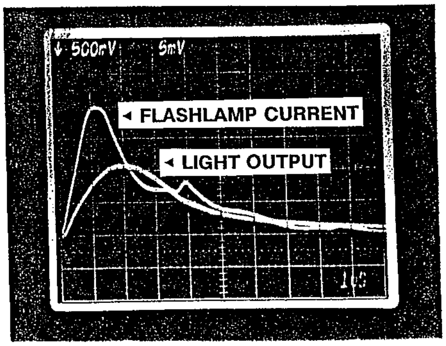

Figure 6. Flashlamp Current and Light Output

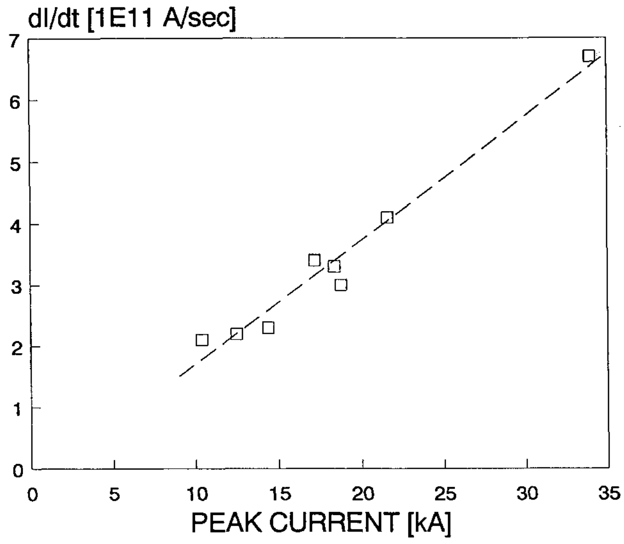

Figure 7. Current Rate-of-Rise

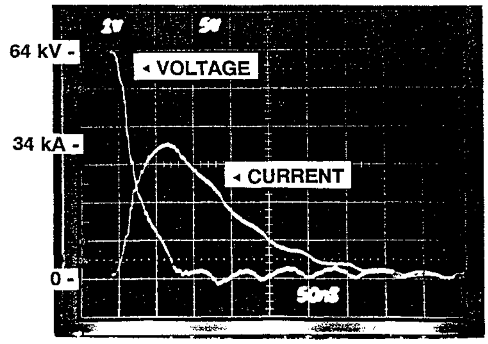

Figure 8. Voltage and Current Waveforms used to determine Switch Losses

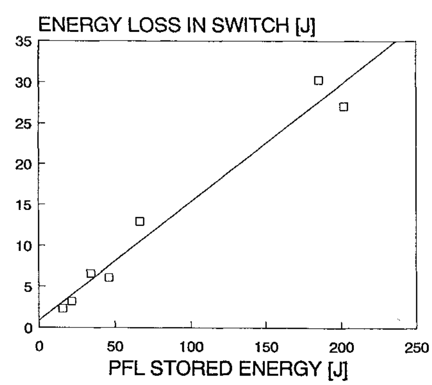

Figure 9. Switch Losses

Two-Pulse Recovery

Two-pulse, switch-recovery time provides a measure of the maximum repetition rate at which a switch can operate. A two-pulse charging circuit was used in conjunction with the PFL test circuit to perform these tests. The recovery test sequence is as follows: With the PFL charged, the test switch is triggered; a preset time later, voltage is reapplied across the switch by again charging the PFL. If the switch does not break down, allowing the PFL to fully charge, the test switch is said to have recovered. The minimum time between switch triggering and full build-up of charge voltage is defined as the recovery time.

The recovery behavior of the test BLT as a function of switch pressure and peak applied voltage is shown in Figure 10. The best recovery time, 600 μs, occurred at the lowest test pressure, 200 mTorr (26.7 Pa). Recovery time increased with voltage for the higher pressures (300 mTorr and 400 mTorr), but remained relatively constant with voltage in the 200-mTorr case.

Improved recovery at lower pressures is typical of low-pressure switches such as thyratrons and pseudo-spark switches. This occurs because recovery is limited by the time required for ambipolar diffusion of the electrons and ions to walls and electrodes. Lower pressure allows this to occur more rapidly. Higher voltage and higher current in the test circuit could result in higher temperatures in the electrode surface and in the gas, requiring them to cool for complete recovery. At lower pressure, gas temperature would have less of an effect, since the collision probabilities are lower.

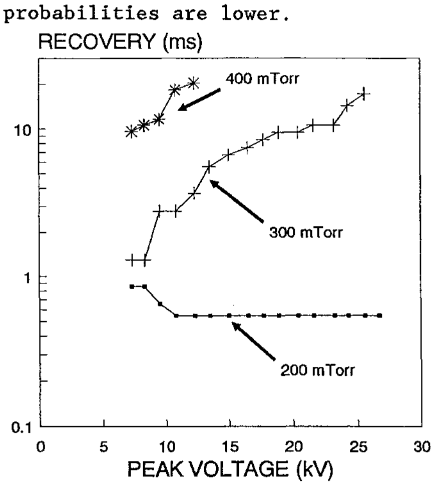

Figure 10. Two-Pulse Recovery

Rep-Rate Testing

Using the low-impedance RLC circuit of Figure 2c, the test switch was operated at rep-rates of 1 to 20 Hz, at an average power of approximately 50 W to 1 kW. The circuit current is a damped sinusoid (Q = 2.1) with an oscillating frequency of 384.6 kHz. These tests were conducted at a switch pressure of approximately 250 mTorr (33.3 Pa), and at three discrete sets of conditions for capacitor charge voltage, peak current, and rep-rate: (1) 15 kV, 10.9 kA, 1 Hz; (2) 15 kV, 10.9 kA, 20 Hz; and (3) 20kV, 14.5 kA, 10 Hz, respectively.

Regardless of operating conditions, the switch failed to recover and latched on at a point hundreds, or sometimes thousands, of shots into each test run. Given the narrow pressure range where the recovery time is short and the voltage holdoff is high, it is likely that the reason for this behavior is an increase in pressure due to switch heating, which causes both recovery and holdoff to drop. Because in these tests the BLT with the built-in reservoir to the hollow cathode was used, it is likely that reservoir heating (which releases hydrogen) may have contributed to an increase in switch pressure.

These tests were terminated after approximately 13,000 shots when the switch became difficult to trigger. The failure mode of the test devices was metalization of the sapphire window, which occurred during rep-rate operation.

Conclusions

Sealed, ceramic-metal BLTs manufactured under controlled conditions have demonstrated exceptional voltage holdoff performance at lower switch pressures: 75 kV at 120 mTorr for a single-gap device. However, at these low pressures the device was more difficult to trigger, and switch delay and jitter increased. It is likely that these difficulties can be overcome by using a UV trigger source that concentrates light near the cathode hole, such as a laser or a flashlamp/laser-powered fiberoptic cable [3].

Delay and jitter, even at higher pressures, were found to be relatively high. This appears to be caused, at least in part, by the relatively slow risetime of the flashlamp (~2 μs). Reducing this risetime has resulted in lower delays and jitters[3].

Results from these tests support the present view[1] that electrode heating contributes to the characteristics of high-current, pseudo-spark discharges. The substantial energy dissipated in the switch, which increases linearly with switched energy, is presumably energy that is used, at least in part, to heat electrode surfaces. The hot electrode surface provides a source of electrons that help support the desirable, high dI/dt switch characteristic. A negative consequence of this type of discharge is that the recovery times increase due to both the longer diffusion times of the heavier metal ions and the time required for the hot surfaces to cool.

In a continuous operation mode, the heat dissipation in the switch is believed to have caused the switch pressure to increase, which in turn caused the switch to latch-on many shots into a given test run. In addition, the heated gas will have more excited states occupied, making it easier to ionize.

Further evidence that metal vapor is present in the pseudo-spark discharge is the electrode material deposition inside the hollow cathode. This metal deposition reduces the life of BLTs that rely on an optically transparent window into the hollow cathode for triggering. Metalization was the failure mode of the switches in these tests.

References

[1] G. Kirkman-Amemiya, et al., "A Study of High Current Back Lighted Thyratron and Pseudospark Switch," Proc. of Nineteenth Power Modulator Symposium, pp. 254-259, June 1990.

[2] J. Bernardes, "A High-Power Fast-Response Switch-Testing System," Proc. of 7th IEEE Pulsed Power Conference, pp. 308-311, June 1989.

[3] K. Frank, et al., "High Power Pseudospark and BLT Switches," IEEE Trans. Plasma Science, vol. 16, no. 2, p. 321, 1988.